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A new assessment model of social cost of carbon and its situation analysis in China

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ABSTRACT

The social cost of carbon (SCC) represents monetary value of the damage caused by carbon dioxide emissions in climate change. It is an important standard for the formulation of climate policy. The uncertainty of carbon social cost is closely related to climate sensitivity, damage parameters, discount rate and so on. Previous studies have mainly focused on the consequences of climate change and the effect of social cost of carbon and welfare under different policies. Its research on the social cost of carbon has not included the evolution coefficient of carbon emissions, and it has rarely introduced the climate disaster damage function into the process of solving the social cost of carbon. This paper provides a simplified formula for the social cost of carbon. The model has a nonlinear processing of the carbon circulation system, which increases the nonlinear structure of CO2 emission potential. In addition, the model modifies the climate damage function, which adds additional losses from climate catastrophes. This paper analyzes the combined effects of several key sensitivity parameters, resulting in a “fat tail” distribution of social cost of carbon ultimately. It is found that the mean SCC of 2015 is 44.93 €/tCO2 and the median SCC is 15.9054 €/tCO2. Considering the possibility of extreme results and the impact of disaster risk loss on uncertain structure, the joint effects of damage parameters, climate sensitive parameters, and discount rates make the social cost of carbon as much as 2.8 times the median and fat tail effect is obvious. This brings uncertainty to the current emission reduction policies and abatement costs, making it more difficult to assess cost-effectiveness. At last, the paper evaluates the social cost of carbon under the base situation and low discount rate in China.

1. Introduction

In recent years, climate change issues such as global warming and rising sea levels have become increasingly prominent and have aroused widespread concern in the international community. Countries around the world have adopted a series of climate change policies to deal with climate change. Pindyck R S(2016)'s analysis of the damage caused by global warming, through the analysis of the discount rate, shows that the climate change problem is becoming more and more serious, and everyone is keenly concerned about a series of cost issues brought about by climate change. Guivarch C, Pottier A. (2017) and others also believe that global warming will have an impact on socioeconomic damage and welfare. The main factor causing climate change and global warming is the increase of global carbon emissions. This is another explanation for the externality of greenhouse gas emissions such as carbon dioxide. The social cost of carbon is the monetary value of the social cost of greenhouse gases such as carbon dioxide, which is of great significance for the formulation of climate policy. Cap-and-trade and carbon tax regulations are the two main low-carbon policies to curb carbon emissions. And the optimal tax rate is decreasing (increasing) or constant in the environmental damage coefficient (Xu et al., 2016).

Currently, increasing energy production is associated closely with increasing fossil-carbon emissions. Despite concerns about carbon emissions in the atmosphere, fossil fuels are likely to remain the main source of primary energy for a long time. In order to prevent climate crises in the long run, On the one hand, new technologies such as carbon capture and storage that mitigate

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large-scale greenhouse gas emissions are being developed. Taking into account both the uncertainty of technological change and damages of climate change, Wang found that different climate damage risks do not affect the optimal technology investment decision. And low carbon technology synergistic strategy is conducive to enhancing the level of CO2 abatement and reducing the total social cost (Wang, K. et al., 2018). Most of the CO2 storage programs are still in the early stages of technological development and are still far from large-scale commercialization (Zhang and Huisingh, 2017). On the other hand, appropriate climate policy interventions (such as the formulation and timing of various carbon tax/trade plans) must be necessary for promoting the development of low-carbon fossil products and accelerating the transition to a post-fossil carbon society (Huisingh et al., 2015). Social cost of carbon is one of the expressions of carbon price, which is closely related to the development of carbon tax. The estimation of social cost of carbon provides an effective analysis tool for government departments to carry out cost-benefit analysis on the regulation of carbon emissions. The higher the cost of carbon society, the more stringent climate change measures governments can take to reduce carbon emissions, such as the formulation of a high carbon tax. Therefore, it is necessary to study SCC for the correct formulation of climate policies.

The cost of carbon emissions has three main concepts: the Social Cost of Carbon, SCC; the Marginal Abatement Cost, MAC; shadow price of carbon emissions. SCC represents the damage caused by carbon dioxide emissions from climate change in monetary terms. In addition, considering the effects of greenhouse gases such as carbon dioxide in the atmosphere accumulate over time, it also translates future damage from carbon dioxide emissions into present values. The marginal abatement cost reflects the marginal cost of reducing carbon dioxide emissions rather than the value of damage caused by emissions. SCC estimate is a function of both the total emission level and the temperature increase, and costs related to one ton of CO2 therefore depend on the timing of the emissions. As for the MAC curve, the more abatement is made the more the abatement cost increases at the margin. The point MAC equals to SCC can be understood as the best emission level. If we reduce emissions and reduce costs less than loss costs, it is worth further reducing emissions. On the other hand, if our emission reduction exceeds the best level, the cost of emission reduction is higher than that of avoiding losses. In principle, this is the right carbon value (Isacs and Finnvenden, 2016). The shadow price of carbon emissions is equal to the marginal social damage under the optimal emission level of carbon dioxide. Under this carbon emission level, the marginal abatement cost of carbon emissions will be equal to the marginal damage of carbon emissions.

In this paper, we use a simpler new model to calculate the social cost of carbon. It does not need to run the entire complex IAM model. This simplified SCC calculation method can obtain an SCC distribution from the original climate-economic uncertainty. The innovation of this paper lies in the new construction of the carbon cycle system, which increases the nonlinear structure of carbon dioxide emission potential; considering that the impact of climate catastrophe on economic damage is enormous, adding additional losses caused by climate catastrophe; optimizing key sensitivity parameters and using this SCC formula to estimate Chinese social cost of carbon. In addition, this paper analyzes the social cost of carbon under multi-parameter uncertain conditions. The remainder of this paper is organized as follows. The relevant literature is reviewed in Section 2. The basic model is established in Section 3. Model parameters overview are given in Section 4. The main results of Comparison and application of simulation results are presented in Section 5. Section 6 concludes the paper and discusses the limitation of this paper.

2. Literature review

Many scholars and experts have conducted in-depth research on SCC in order to develop better climate policies in cost-benefit analysis. The IAM model is the mainstream model for calculating social welfare maximization and SCC. Nordhaus (1991) combined the climate ecosystem with the economic system in a model framework to evaluate climate policy, marking the beginning of the IAM model.

In 2009, the Obama administration set up an Interagency Working Group to assess how to maximize the benefits of carbon reduction. Accordingly, the departmental joint task force investigated previous literature and assigned a series of quantitative values to the social cost of carbon used in the official policy analysis. In advancing this task, the working group adopted three major IAM models: Nordhaus' “Dynamic Integrated Climate Economy” (DICE) model (Nordhaus, 2008); Hope's “Policy Analysis of the Greenhouse Effect” (PAGE) model (Hope, 2008); and Tol's “Climate Framework for Uncertainty, Negotiation, and Distribution” (FUND) model (Tol, 1997). The modeling ideas of these three models are consistent. CO2 emissions are converted to concentrations in the atmosphere through the atmospheric carbon cycle. Increasing gas concentrations are translated into climatic temperature increments through the climate equation. The increase of atmospheric temperature leads to economic loss, and then the analysis of income from the sustained economic loss and the effect of reducing carbon emissions. Although these models differ in their details, they have adopted similar expressions to describe the emission reduction costs of greenhouse gas emissions, the impact of climate change on the economy, the future trends in technology, population and economic growth. The DICE model is one of the earlier and widely used models. This model is an integrated model of economic and climate dynamics that integrates factors such as climate change, population, capital, carbon emissions, and carbon cycle. The SCC estimated by the DICE model is the best way to establish CO2 emissions and capital investment based on maximizing the objective function. Cao thought that the carbon emission reduction level increases as the carbon trading price increases, whereas it is independent of the unit low carbon subsidy. They found that low carbon subsidy policy is more beneficial to society when the environmental damage coefficient is less than a threshold (Cao, K. et al., 2017).

Gerlagh and Liski (2012) analyzed the carbon price in the discrete time state. Pindyck (2016) abandoned the method of using the IAMS model to find marginal carbon social costs. The average SCC is estimated by the ratio of the damage present value of the extreme result to the total emission reduction required to avoid the result. In the calculation of loss present value, the tail value affecting SCC distribution is abandoned. Meanwhile, it is found that the sensitivity of average carbon social cost on discount rate is far lower than that of marginal carbon social cost. Dayaratna and Mckitrick. (2017) included a new estimate of the equilibrium climate sensitivity distribution in the DICE model, which is found that the use of well-defined sensitivity parameters can also reduce the uncertainty associated with the choice of discount rate, The estimates of carbon social cost produced are much lower than the carbon social costs of models based on simulated equilibrium climate sensitivity parameters.

The Intergovernmental Panel on Climate Change (IPCC) had argued that Earth could be 4.8°Cwarmer by 2100(IPCC, 2011). The frequent occurrence of extreme weather, the decrease of crop production and the rise of sea level are all directly related to the carbon emissions in human activities. The scientific community has carried out a series of explorations from different perspectives on the study of the uncertainty of SCC and disaster risk.

Simon Dietz (2011) provided some empirical tests of key theories. The key parameters of climate sensitivity and economic cost in the probabilistic comprehensive assessment model obey the thick-tailed distribution. The results show that the welfare estimates are strongly dependent on the tail risk. This uncertainty makes the calculations of SCC need to consider the possibility of a fat-tailed distribution of extreme values. The fat tail distribution is a kind of probability distribution model, which is thicker than the tail of the general normal distribution and pointed at the peak. Intuitively speaking, it is the probability that the extreme value of the data is greater than the probability of the extreme value of the normal distribution. Weitzman (2007) argued that uncertainty can mask the effects of different consumer discount rates, especially the possibility of catastrophic climate risk. In addition, we cannot exclude the extreme consequences of climate change. The distribution of economic growth will be a fat tail distribution, which will have a huge impact on the results of cost-benefit analysis. This means that considering the influence of the fat tail distribution, the existence of extreme values in the calculation of the social cost of carbon makes the final SCC larger. Ackerman et al. (2010) used DICE model to examine the influence of the fat-tailed probability distribution of climate sensitivity parameters. It is found that the characteristics of the uncertainty of climate and damage have a significant impact on policy recommendations. They believe that independently changing the climate sensitivity parameter or the impairment function index has little effect on the optimistic prediction of the DICE model. Gerst et al. (2010) used a dynamic stochastic general equilibrium model to explore the consequences of climate change and the welfare impact of climate change mitigation policies. The model considers the “fat tail” in terms of climate sensitivity and the cost of climate change damage, reflecting the possibility that it is impossible to exclude extreme results.

Recent articles have recognized the importance of climate sensitivity, climate damage and the uncertainty of discount rate, and used the IAM model to explore the effects of critical parameter uncertainties on welfare and disaster risk. For example, Ackerman et al. (2010) and Gerst et al. (2010) explored the uncertainty of climate sensitivity parameters and the possibility of damage risk. However, the possibility of disaster risk, the structural uncertainty of damage, key sensitivity parameters and dynamic welfare discount rate are difficult to quantify. The existing literature have less structural analysis of the impact of these key parameters on the social cost of carbon. What's more, the previous literature on the study of social cost of carbon did not include the evolution coefficient of carbon emissions. In the structure of the formula, this paper not only considers the nonlinear structure of the carbon cycle system, adding the carbon emission evolution coefficient, but also modifies the climate damage function, which adding additional losses caused by climate catastrophes. Finally a new model of carbon social cost is constructed. In addition, the paper analyzed the social cost of carbon under the uncertainty of multiple parameters.

Through simulation analysis, the median SCC calculated in this paper is 15.9594 €/tCO2, similar to the 15 €/tCO2 of Bijgaart et al. (2016). But the mean SCC is 44.93 €/tCO2, which is greater than the 31 €/t CO2 calculated by Bijgaart et al. (2016). With the similar median SCC, the larger mean SCC makes the density of new social cost of carbon distributed into a fat tail distribution, and resulting distribution of the right-skewed is more serious than that of Bijgaart et al. Due to the greater consideration of the possibility of extreme results and the impact of disaster risk damage on uncertain structures, the mean SCC is finally 2.8 times the median value, and the fat tail effect is obvious.

Based on the calculation of SCC in this paper, in the baseline scenario, China's social cost of carbon in 2015 is about 9.20 $/tC. In the low discount rate scenario, China's social cost of carbon in 2015 is approximately 16.35$/tC. By considering the current situation of China's regional carbon emissions, the trend of rising temperature and the situation of economic development, this paper modifies the relevant parameters and initial data on the basis of the new model, which makes the model more consistent with China's regional development, and provides theoretical and model support by finding the carbon emission path of the different standard.

3. New evaluation model

SCC can be obtained by a comprehensive evaluation model calculated. This paper extends the modeling idea of Nordhaus. (2008) and provides a simplified and closed form formula to explore the key physical and economic factors of SCC in the IAMS. The changes of structure captured by the formula have the consistent SCC distribution with the previous SCC estimates. The construction of the model allows us to evaluate the most important sources of the uncertainty of SCC, and the formula gives a structural explanation of the SCC distribution. $Y(t)$is the world total output of time$t$, and$\chi$is the damage sensitivity coefficient to the increase of carbon dioxide in the atmosphere, and then the formula of social cost of carbon assessment model is as follows:

$$SCC(t) = \chi Y(t) \sum_{i \in I} \frac{a_i \epsilon}{(\eta_i + \sigma)(\epsilon + \sigma)} \left(1 - \frac{2E(t)}{n \cdot k_e}\right)$$

The estimation of carbon social cost is obtained by optimizing the current emissions in the global carbon cycle and the global economic-related temperature dynamic model. Therefore, the reasonable establishment of carbon cycle model is one of the important factors that affect the simulation results of the comprehensive assessment model. Since the effects of climate change and environment impact caused by the greenhouse gases emissions are always occurring, it is more reasonable to use a continuous time function to characterize the circulation and accumulation of carbon. Based on this, Bijgaart et al. (2016) characterize the carbon cycle in a continuous time state. The carbon cycle structure is as follows:

$$S(t) = \sum_{i \in I} S_i(t),$$
$$\dot{S}_i(t) = a_i E(t) - \eta_i S_i(t),$$

Here $S(t)$ is the carbon dioxide that is beyond the level of industrial reserves at time t, and $a = (a_i)_{i \in I}$ is the vector shares of carbon emissions entering each climate box. A unit value of$a_i$means that the carbon dioxide emitted per ton converted to the concentration of carbon dioxide of one ton of atmosphere in the atmosphere; $\eta_i$is the attenuation rate of the box. It assumes that the carbon stock in the atmosphere slowly decays and is gradually absorbed by the ocean, soil, etc. $E(t)$ is carbon emission at time$t$.

Tian L and Jin R (2012) analyzed the evolution of carbon emissions, and a nonlinear carbon emission evolution system is constructed from the basis non-linear influence. This paper combines Bijgaart et al.'s research on carbon cycling, and make a non-linear treatment for the carbon cycle model. The carbon cycle structure is as follows:

$$\dot{S}_i(t) = a_i E(t) \left(1 - \frac{E(t)}{n \cdot k_e}\right) - \eta_i S_i(t)$$

In which,$S(t)$, η_i and $E(t)$ have the same meaning as the symbols in the above carbon cycle structure. $k_e$is related to the time interval, which indicates the maximum amount of carbon emissions in the time period of study, an n is the evolutionary coefficient of carbon

emission, here$n = 1$; k_e is taken as an estimate of the total amount of carbon emissions before 2100. Comparing with the previous literature, it is considered that emitted carbon dioxide changed into the concentration of carbon dioxide in the atmosphere is nonlinear, and the structure of $\left(1-\frac{E(t)}{n\cdot k_e}\right)$ is added. Carbon dioxide reserves at time$t$are not only related to the concentration of carbon dioxide $a_iE(t)$in the atmosphere, but also in proportion to the share of carbon dioxide emission potential,$\left(1-\frac{E(t)}{n\cdot k_e}\right)$.

Multiple iterations of the carbon cycle formula, so carbon reserve in the atmosphere$S(t+\tau)$of time $t+\tau$about the carbon emissions at time$t$for differentiating is obtained:

$$\frac{dS(t+\tau)}{dE(t)} = \frac{d\sum_{i\in I}S_i(t+\tau)}{dE(t)} = \sum_{i\in I} e^{-\eta_i(\tau-1)}a_i\left(1-\frac{2E(t)}{n\cdot k_e}\right)$$

In DICE or other comprehensive assessment models, climate damage is a convex function $D=\varphi(T)$ of the temperature rise$T$. At the same time the concentration of the atmosphere increases, making the temperature and concentration of$T=\phi(S)$, which can be obtained:

$$D(t) = D(t-1) + \epsilon[\chi S(t) - D(t-1)]$$

The emission $E(t)$ increases the CO2 reserves in the atmosphere. Through the carbon cycle, there is a linear relationship between the steady-state level of CO2 in the atmosphere and the degree of damage. The linear coefficient isχ, that is, each additional unit of atmospheric carbon dioxide concentration results in the damage increment of χ unit. The damage of the t period is the sum of the damage in period$t-1$and the increment of damage caused by carbon emissions during this period. The warming of CO2 is not instantaneous. The increment of damage is synchronous with rising temperature. $\epsilon$is the coefficient of temperature adjustment, and it is the time delay coefficient of CO2 concentration converted to rising temperature.

Multiple linear substitutions for the climate damage formula. We can get the extent of the current emission damage $Z(\tau)$over the periodτ, that is:

$$Z(\tau) = \frac{dD(t+\tau)}{dE(t)} = \chi\sum_{i\in I}a_i\epsilon\frac{e^{-\eta_i\tau}-e^{-\epsilon\tau}}{\epsilon-\eta_i}\left(1-\frac{2E(t)}{n\cdot k_e}\right)$$

Because the damage caused by climate change depends on the historical carbon emissions, here we define $Z(\tau)$ as "emission-temperature response function". That is, the effect of the current emission $E(t)$ on the temperature change at time $t+\tau$ is depicted by$Z(\tau)$.

Considering carbon dioxide and other greenhouse gases in the atmosphere will accumulate over time, the net present value of future damage, calculated by the discount rate, is expressed as the net present value of the future damage caused by the carbon emissions per unit at time$t$. The social cost of carbon is expressed as:

$$\begin{aligned} SCC(t) &= Y(t)\int_0^\infty e^{-\sigma\tau}\frac{dD(t+\tau)}{dE(t)}d\tau \\ &= \chi Y(t)\sum_{i\in I}\frac{a_i\epsilon}{(\eta_i+\sigma)(\epsilon+\sigma)}\left(1-\frac{2E(t)}{n\cdot k_e}\right) \end{aligned}$$

In which, $W(\cdot)=\sum_{i\in I}\frac{a_i\epsilon}{(\eta_i+\sigma)(\epsilon+\sigma)}\left(1-\frac{2E(t)}{n\cdot k_e}\right)$ is the economic life of damage in the atmosphere under the combined action of carbon cycle, temperature regulation, and discount rate.

It is assumed that the social cost of climate change is a smooth function of income, damage and temperature rise. Most integrated assessment models assume that damage is proportional to income, and the trajectory of SCC will increase roughly with the income level. $\chi$is the percentage of output damage caused by a unit of CO2 in the atmosphere. $\chi Y(t)$represents annual economic losses resulting from the fixed growth of a unit of CO2 in the atmosphere. The last part of the formula is determined by the discount rate, the carbon cycle parameter, regulation parameter of the temperature, the parameter of carbon emission and the economic index. The most complex part of the model is to calculate the economic life of damage based on the global carbon cycle and the delay of discounting factor. Under the control of global temperature, the change of temperature lags behind the concentration of carbon dioxide in the atmosphere. The new model constructed in this paper adds the impact of carbon emission indices on the damage to the economic life in the last term of the formula. The damage economic life of the new social cost of carbon formula not only considers the decrease of the net present value of the economic damage caused by the temperature delays, but also puts the carbon emissions into the formula. The damage factorχ in the formula also increases the impact of climate catastrophe on climate damage. In addition, the new formula also provides a way to calculate the social cost of regional carbon.

4. Model parameters overview

SCC is an important reference index for the internalization of the negative externalities of greenhouse gases, such as carbon dioxide. The calculation of the social cost of carbon involves a number of climate change parameters and sensitivity parameters. The cost of carbon emissions changes over time and the future damage will be discounted by monetization, which involves the issue of discount rate.

4.1. Parameters of discount rate

The abatement cost function and damage function of the integrated assessment model involve the problem of discount rate. The discount rate is determined by three parameters: pure time preference rate, elasticity of consumption marginal utility and consumption growth rate. The discount rate affects the social welfare function and determines the path of emission reduction eventually. Discount rate refers to future "utility" or welfare benefit discount, not to the future goods or dollars.

The value of the discount rate directly affects the analysis of climate change conclusion and the response policy. The value of the discount rate directly affects the analysis of climate change conclusion and the response policy. In the case of high discount rate, the discount of future damage is small, so it tends to chronic emission reduction, and then gradually increases the intensity of emission reduction. However, in the case of low discount rate, the future damage is a larger present value. So the government is more likely to adopt radical emission reduction policies and drastically reduce current greenhouse gas emissions.

According to the discount rate of the DICE model, this paper uses the modified the formula of discount rate to describe the present value of the future damage. The revised discount rate σ is expressed as:

$$\sigma = \rho + (\eta-\xi)g - l$$

Assuming that the rate of population growth is, l the population growth rate will be subtracted from the pure discount rate when

more people are affected by climate change in the future. Climate damage is assumed to be elasticξ as output changes. With economic growth, the marginal value of future damage will be decreased, and the marginal utility elastic will be reduced from η to$\eta - \xi$. When there is no uncertainty or the short and medium-term economic growth is relatively determined, the Ramsay formula under fixed growth conditions determines the discount rate. While in the long run, the growth of the population, the marginal elasticity of the future damage and all the items together determine the value of the discount rate.

At present, China still uses a fixed discount rate for the measurement of public investment. Wang et al. (2013) used the SRTR method to calculate the social discount rate in our country, which shows that the reasonable value of the social discount rate in China in 2011 should be 4.5%. This paper refers to Wang et al.'s article and combines the changes in the growth rate of consumption over the next five years. Therefore, we assume that China's average consumption growth rate for 2015–2020 is 5.5%. With the decrease of Chinese population mortality rate and the relaxation of child policy, the population growth rate of China has gradually increased, assuming that the average population growth rate of our country in the next five years is 6‰. The value of marginal utility of consumption elasticity coefficient in Table 1 is 2. Nordhaus (2007) and Stern (2007) have heated debate about the annual rate of social time preference. Based on the research of various scholars, the improved model adopts the rate of pure time preference defined by Nordhaus with a value of 0.015. In the fourth part, the scenario analysis is conducted with the discount rates of 0.1%, 1%, 2%, 3% and 4%.

4.2. The parameters of carbon emission

In 2015, the total global emissions of fossil fuels and industrial carbon dioxide almost equals to those in 2014, at approximately 9855 million tons. The data of carbon dioxide emissions comes from Carbon Dioxide Information Analysis Center, (CDIAC) and the IPCC Fifth Assessment report (2013). The future global CO2 emissions space is an extremely complex and controversial topic. The IPCC Fifth Assessment Report provides different typical concentration pathways based on climate prediction. This paper chooses the middle scene RCP4.5. In this scenario, the global emission space for the 2012–2100 year was 780GtC, i.e. the maximum estimation for the total carbon emissions by 2100 was 780 billion tons.

From a global perspective, some climate parameters are constant over a short period of time. Therefore, the climate change parameters in the DICE model are used in this paper (Nordhaus, 1994). The annual global greenhouse gases report published by WMO shows that the major greenhouse gas concentrations in the global atmosphere continue to break through the historical records of instruments observed. The concentration of carbon dioxide is 400.0 ± 0.1 ppm in 2015. The report confirms that 2016 is the hottest year in climate record history, the temperature is 1.1 °C higher than the level before industrialization and 0.06 °C higher than in 2015.

4.3. Damage sensitivity parameters

Gerlagh and Liski (2012) regard the climate damage D as a part of the global output and set the increase in temperature since the standard year as$T$. It is considered that the damage should be a quadratic function of the temperature rise. Because the impact of climate disaster on economic damage is enormous, Nordhaus has improved the model on the basis of the Nordhaus' DICE-2013 model. Here, we add the climate damage function to the additional damage caused by the climate catastrophe. Therefore, the modified function of regional climate damage is used in this paper, and the structure is as follows:

$$D(t) = \varphi(t) = \nu_1 T + \nu_2 T^{b^1} + \nu_3 (T/T_{TP})^3$$

The third item reflects the additional damage caused by the climate disaster. $\nu_1, \nu_2$are sensitivity parameters of regional economic damage, the damage parameters of China are directly applied to the formula in the RICE model. The damage function is a convex temperature response function that depends on the concentration$S$. $c$is a climate sensitive parameter. As the temperature changes, the damage substantially increases.T_{TP} is the threshold of the climate disaster, set $T_{TP} = 4°C$, $\nu_3 = 0.00644$ .Compared frequent losses and relatively small amount of loss with the general climate damage, the probability of climate disaster is low, once it happens, it often causes great damage. Thus the risk distribution of climatic disaster is typical fat-tailed distribution. The impact of this uncertainty is intuitive. Even though disaster risk possibility may be very small, as long as it is the fat-tailed distribution, people are always willing to reduce current consumption or investment in reducing emissions based on precautionary principle, to avoid the extreme events such as climate disaster. Suppose that $\chi = \varphi'\phi'$and$dD = \varphi'\phi'(S)dS$, the sensitivity parameter χ of the regional damage can be expressed as:

$$\chi = \frac{\nu_1 c}{\ln(2)(S+m)} + 2\nu_2 c^2 \frac{\log_2(1+S/m)}{\ln(2)(S+m)} + \frac{3c^3\nu_3}{T_{TP}^3}\frac{[\log_2(1+S/m)]^2}{\ln(2)(S+m)}.$$

Consider the possibility of the climate catastrophe, the structure of the revised regional damage $Z(\tau)$ in the current emission period τ is as follows:

$$Z(\tau) = \frac{\nu_1 c}{\ln(2)(S+m)} + 2\nu_2 c^2 \frac{\log_2(1+S/m)}{\ln(2)(S+m)} + \frac{3c^3\nu_3}{T_{TP}^3}\frac{[\log_2(1+S/m)]^2}{\ln(2)(S+m)}\sum_{i\in I} a_i \epsilon \frac{e^{-\eta_i\tau} - e^{-\epsilon\tau}}{\epsilon - \eta_i}\left(1 - \frac{2E(t)}{n \cdot k_e}\right)$$

5. Comparison and application of simulation results

5.1. Damage delay under different carbon cycles

The impact of climate change on gross domestic product or consumption is expressed by the loss function. The increment of a unit of carbon dioxide is not caused by instantaneous changes, due to atmospheric temperature regulation, carbon cycle accumulation, and the damage caused by the increase of carbon dioxide will appear in the lagging decades. Table 1 shows the carbon cycle parameters based on the MR-H (Maier-Reimer and Hasselmann, 1987), GL (Gerlagh and Liski, 2012), and DICE model(Nordhaus, 2008).

Where ϵ is the temperature adjustment speed, which is the same as the parameter values in the DICE model, equal to 0.02(Nordhaus, 2008). T is the increment of current temperature. $\phi(S)$ is the increment of cumulative balance temperature, and the other parameters are obtained as described in Table 1. Fig. 1 (a) is the world's output loss response image, and Fig. 1 (b) is China's output loss response image. The two images show that the loss of the carbon cycle parameters about three kinds of models increases first and reaches the maximum value in about 100 years, and then the output loss will gradually decrease over time. And the peak of

Table 1
Carbon cycle parameters of the Models.

Carbon cycle parameters		
Model	Share of emissions entering climate box	Climate box i carbon depreciation rate $(\eta_i)_{i\in I}$
GL(2012)	(0.163,0.190,0.589)	(0,0.0076,0.0618)
DICE(RICE)	(0.029,0.356,0.615)	(0,0.0035,0.0364)
MR-H	(0.142,0.241,0.323, 0.206,0.088)	(0,0.0032,0.0125,0.0532,0.5882)
Mean fit[a]	(0.119,0.308,0.573)	(0,0.0047,0.0470)

[a] Obtained by minimizing the squared deviation from the mean of the MR-H, DICE and GL response functions.

China's climate damage under the same carbon cycle is lower than the peak value of global damage. In a longer period, the loss value of the carbon cycle parameters of the DICE model is much smaller than other carbon cycles. The change of temperature affects the severity of economic damage. It also illustrates the general curve of temperature time response function indirectly. The ratio of output damage to DICE carbon cycle parameters in Fig. 1 (a) is much larger than Gerlagh and Liski (2012) DICE carbon cycle models. The reason is that this paper deals with the non-linear process of carbon cycle model, which takes the share of carbon dioxide emission potential into the carbon cycle structure, while the climate sensitivity parameter increases the amount of extra extreme risk. The peak of the damage response is about 70 years behind the emission date, which means that economic losses will increase to a peak in the next few decades. Current carbon emissions have not brought a significant impact in the short term, but the current impact of emissions reductions intensity and abatement cost on GDP is obvious. This will lead to a lot of uncertainty for the government to formula emission reduction plans. Delays in carbon emissions, risk aversion and other factors will also affect the use of carbon emissions by consumers.

5.2. Economic life under different discount rates

The massive emissions of greenhouse gases such as carbon dioxide lead to the accumulation of carbon in the atmosphere, and the accumulation of carbon concentrations requires a long process. The cycle of carbon in the reservoir is spreading, and the delay in climate change is obvious. Fig. 2 shows the nonlinear relationship between the economic life $W(\bullet)$ of atmospheric carbon dioxide emissions and the discount rate under the four carbon cycle models.

Fig. 2 shows that when the discount rate approaches zero, the economic life $W(\bullet)$ tends to infinity. When the discount rate is large enough, the economic life of carbon dioxide is very short. At this point, the effect of discount rate is weakened, and the value of economic life tends to remain unchanged. When the discount rate is 0.1%, 0.5%, 1%, the economic life of carbon dioxide will increase exponentially. The economic life in the atmosphere is composed of carbon cycle, temperature adjustment and discount rate. Economic life $W(\bullet)$is the response function about time, and the weight σ decreases exponentially. Through the$W(\bullet)$ social cost of carbon has been linked to damage, discount rates, and carbon emissions. Fig. 2 shows that the impact of the economic life of the four carbon cycles has the same trend in general. For a single carbon cycle model, the discount rate is a major factor to impact the value of the economic life of carbon dioxide.

5.3. The uncertainty of carbon social cost — "fat-tailed" distribution

Many climatic and economic parameters are involved in the analysis and calculation of the social cost of carbon. The main simulation parameters are: Climatic sensitivity parameter (Dietz and Asheim, 2012); the damage sensitivity parameter (Tol, 2009); the discount rate (Weitzman, 2001). The initial distribution of some parameters of the model is shown in Table 2.

This article only shows the parameter distribution related to the model.

These parameters are also used in the DICE model (Nordhaus, 2008). In this paper, Monte Carlo simulation method is used to obtain the simulation values of the parameters. The values of these simulated parameters are log-normal distributed, and the median and mean values are basically the same as those in Table 2. Then, we simulate the density distribution of SCC by introducing the parameters into the formula, and explore the factors that affect the uncertainty of social cost of carbon. Fig. 3 is a preliminary simulation of SCC, and SCC density distribution is obtained with obvious fat tail distribution.

The structure of the formula about carbon social cost determines that we can construct an SCC density distribution from the original uncertainties such as carbon cycle, climate sensitivity and damage economy. Nordhaus (2011) calculates the discount rate under different scenarios using Ramsey equation. This paper uses the same discount rate estimate to import the Monte Carlo simulation sensitivity parameter values into the SCC formula. Finally, the distribution of SCC at different discount rates shown in Fig. 3 is obtained. Fig. 3 describes the density distribution obtained from

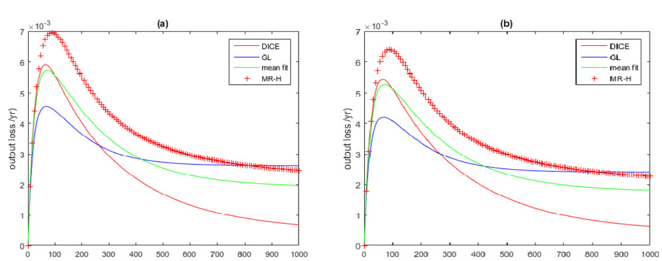

Fig. 1. Output loss delay under different carbon cycles.

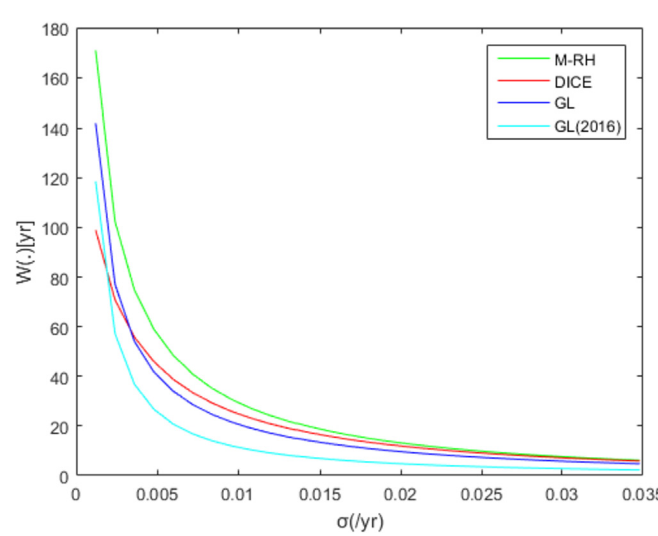

Fig. 2. Economic life under different discount rates.

Table 2

Parameter	Meiian	Mean	Standard Deviation value	Lower Cutoff value	Upper Cutoff value
Climate sensitivity	3	3.218	1.222	1.3719	6.5601
Damage parameter	0.003	0.004	0.0032	0.0006	0.015
Pure time preference rate	0.02	0.0248	0.0171	0.005	0.08
Elasticity of marginal utility	1	1.0845	0.4447	0.4305	2.3229
Pure discount rate	0.018	0.0224	0.0154	0.005	0.072

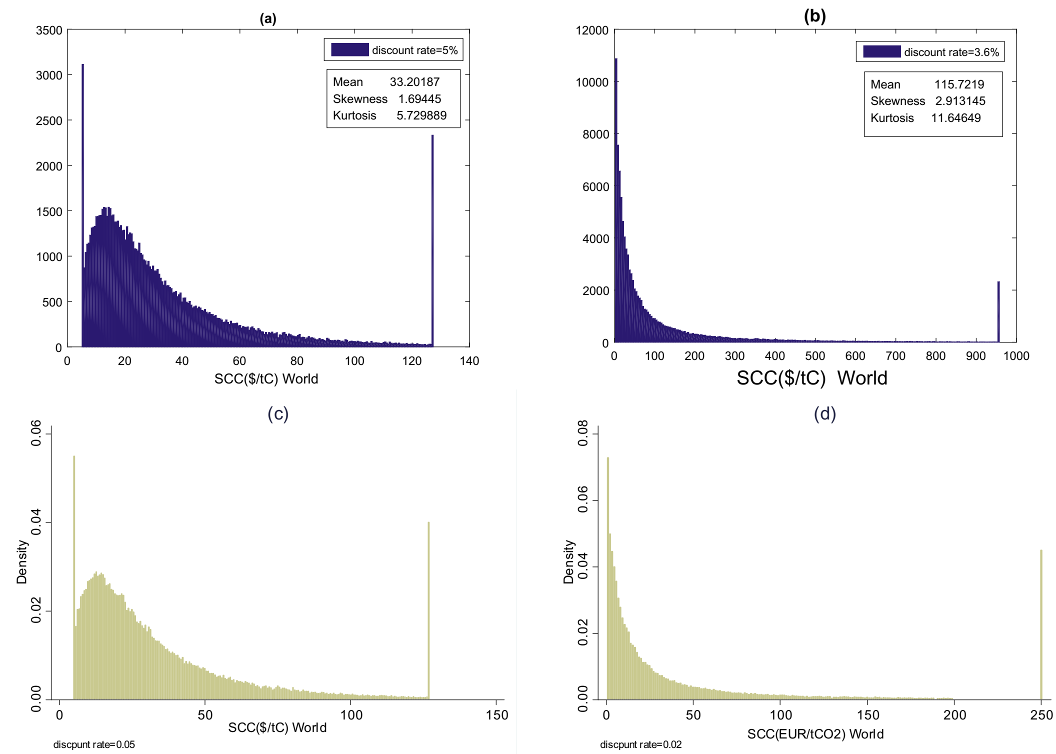

Fig. 3. Density distribution of SCC under different discount rate.

the SCC formula. Fig. 3 (a) is the global carbon social cost distribution of the benchmark scenario. The result of discount rate 5% shows that the median is 24.55$/t C, the mean value is 33.20 $/t C with strongly right skewed. Fig. 3 (b) is a global carbon social cost distribution situation of low discount rate, and the discount rate is 3.6%. The pure rate of time preference is $\rho = 1.5\%$ referred to the relevant literature. The distribution results shows that the median of 40.97$/t C, the mean value of 115.72 $/t C. The skewness of both Fig. 3(a) and (b) is greater than zero, indicating that the SCC distribution is right-biased and the kurtosis is greater than 3, and the distribution of SCC is a sharp peak-tailed distribution. As shown in Fig. 3 (c), the social cost of carbon is 4% more likely to be worth more than 100 $/t C. Combined with Fig. 3(a) and (c), we can find that the average carbon social cost under the baseline scenario with a discount rate of 5% is 33.20 $/t C, while the value of SCC in Fig. 3(c) is highly likely to be greater than 50$/t C. This extreme value of large probability appears, making the SCC distribution thicker than the normal distribution tail, showing a fat tail distribution. Fig. 3 (d) is a discount rate of 0.02, the output from the 2010 Euro calculated density distribution map. The distribution results show that the mean SCC is 44.93€/tCO2. From Fig. 3 (d), we can see that 3% probability of the social cost of carbon is more than 200 €/tCO2. In the case of the discount rate of 2%, the global social cost of carbon is calculated to be a median of 15€/tCO2, and a mean value of 31.5€/tCO2 with right partial distribution by Bijgaart et al. (2016), which is caused by the extreme value of the low probability of mutual strengthening among climate sensitivity, damage and discounting.

Climate change involves a lot of optimization problems. Nordhauds' DICE model and RICE model are typical welfare maximization models. Nordhauds and Us Epa (2015) calculate the carbon social cost through the optimization model to maximize the social welfare. In Social Cost of Carbon, the social cost of carbon is 11 $/tCO2, and its discount rate is 5%. At the discount rate of 3%, the carbon social cost is 36 $/tCO2. In Fig. 4 (b), the discount rate is 3.6%, which is higher than 3%. The social cost of carbon is 115.72$/t C, slightly lower than 138.25 $/t C. Nordhaus (2011) in the scene of the discount rate of 5%, 3.6% calculated social cost of carbon of 44 $/t C, 138 $/t C. The calculation is realistic.

The shape and right-deviation of SCC density distribution calculated in this paper are similar to those of Bijgaart et al.(2016), but the mean SCC of this paper is greater than 31.5 €/tCO2 calculated by Bijgaart et al. This is because the damage response function is updated in this paper. The impact of climate disaster is added to the damage function of the climate zone, resulting in an increase in the value of climate damage caused by one unit of carbon dioxide, which eventually leads to an increase in the value of SCC.

This is because the damage response function has been updated in this paper. The effect of climate catastrophe has been added to the damage function in the climate zone, Based on the analysis of the discount rate and the social cost of the carbon in the RICE (2011)

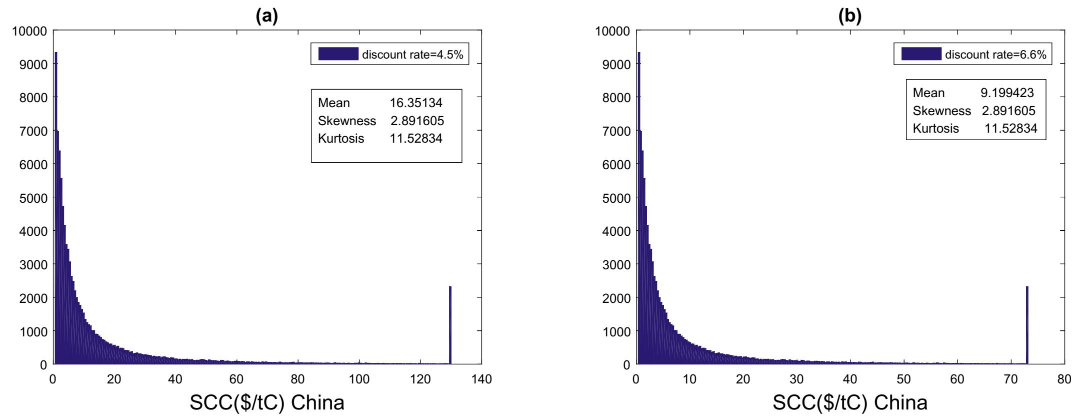

Fig. 4. Density distribution of China's SCC under different discount rate.

model, this paper suppose that the discount rate is 6.6% under the benchmark scenario, the discount rate is 4.5% under the low discount scenario. And the density distribution of China's carbon social cost is obtained by the formula of social cost of carbon as shown in following:

From the Fig. 4 (a), the discount rate is 4.5%, and the distribution results show that the mean SCC is 16.35 $/C with strong right skewed. From the Fig. 4 (b), the discount rate is 6.6%. The result shows that the mean SCC is 9.20 $/C. The time preference rate in the Stern report is 0.1%, and the coefficient of consumption elasticity is 1 per year. In this scenario, the discount rate is very small, which is not conformed to China's discount rate and the actual consumption preference. Therefore, the low discount scenario reported by Stern is not studied in this paper.

5.4. The reasons for the uncertainty of the carbon social cost

The social cost of carbon is the net present value of marginal damage. We assume that the values of other parameters are fixed. Considering the effect of discount rate and different carbon cycle modes on SCC value, we get the Fig. 5:

Fig. 5 shows that the value of the discount rate is crucial for the study of social cost of carbon. When the value of discount rate tends to zero, the social cost of per unit of carbon dioxide is expected to be infinite. When the value of discount rate is large enough, the value of SCC is very small. In this case, the social cost of carbon set on carbon emission will have a weak impact on consumers' emission reduction behavior, and cannot achieve the purpose to control temperature rise by reducing the carbon emission.

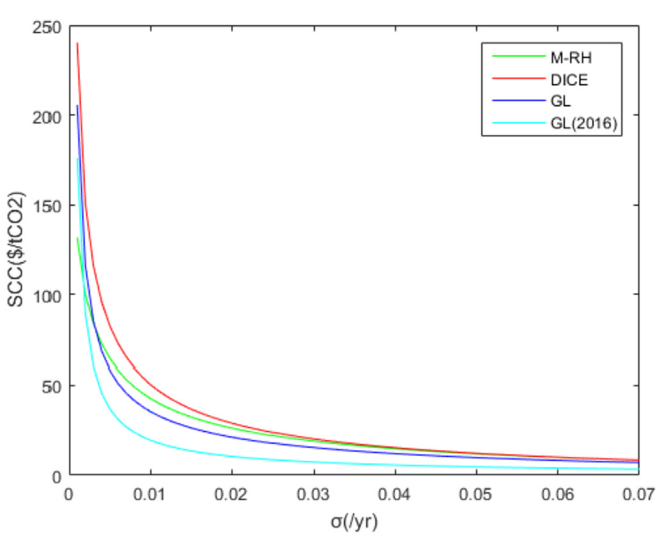

Fig. 5. The social cost of carbon under different carbon cycle.

In order to further study the direct relationship between discount rate and the social cost of carbon, we exclude the interference of different carbon cycle values in Fig. 5, and unified the carbon cycle parameters. Considering only one atmospheric carbon pool in the SCC formula, the CO2 emission attenuation rate and temperature adjustment parameters in the atmosphere are obtained based on the mean value of the literature, i.e. $(a,\eta,\epsilon) = (1, 0.01, 0.02)$. Only considering the impact of discount rate on the social costs of carbon and the result is given in Table 3:

Table 3 shows the median and mean value of Chinese SCC at different discount rates. As for a given climate change, climate sensitivity and output, the formula predicts that the social cost of carbon is proportional to the discount rate. The net present value of a unit of CO2 emissions will double when the discount rate is reduced from 3% to 2%. The corresponding mean SCC and median SCC are almost 2 times larger. The mean SCC and median SCC value are almost 3 times larger, when the discount rate dropped from 1% to 0.1%.

The following consideration is given to the impact of a single parameter on the uncertainty of social cost of carbon. By defining other variables, the numerical effects of a single parameter on the social cost are obtained.

Table 4 shows the impact of a single variable on carbon social costs. When all parameters are taken from the mean value, the result is corresponding to None scenario. At this time, the values of climate sensitive parameter, the damage coefficient and the discount rate are all fixed, and the social cost of carbon is disappeared after the fixed value. When the damage parameter, climate sensitive parameter and discount rate work together, the uncertain structure of carbon social cost is obtained with a fat tail distribution, which ultimately makes the mean SCC 2.8 times the median SCC value. The social cost of carbon median value calculated by Bijgaart et al. (2016) is 14.6€$/tCO_2$, mean SCC is 31.5€$/tCO_2$ and the social cost of carbon is 2 times higher than the median. In contrast to Bijgaart et al. (2016) analysis of the uncertainty of the carbon

Table 3

Discount rate	Obs	Mean($/tC)	Median($/tC)
0.1%	100000	296.0070	113.7205
1%	100000	113.9627	43.7824
2%	100000	56.9813	21.8912
3%	100000	34.1888	13.134745
4%	100000	22.7925	8.7565

Table 4

Source of variation	Obs	Mean(€/tCO2)	Median(€/tCO2)	Std.Dev(€/tCO2)
None	100000	16.3849	16.3849	0
Damage	100000	21.4652	16.2799	16.5508
Climate sensitivity	100000	21.9813	16.2728	18.0376
Discount rate	100000	19.6602	18.1752	13.3059
All	100000	44.9285	15.9054	75.0455

social cost structure, the median SCC of 15.9054 €/tCO2 in Table 4 is approximately equal to the median value calculated by Bijgaart et al. (2016). But the mean SCC is much larger than the mean value calculated by Bijgaart et al. (2016). In this paper, we construct a new model of carbon social cost, which is much thicker than the uncertain structure of carbon social costs in Bijgaart et al. That is to say, this paper considers more about the possibility of extreme outcomes and the impact of disaster risk damage to an uncertain structure.

6. Conclusion

Climate change not only has an impact on contemporary people, as the atmospheric greenhouse gas accumulation, the heating losses will be borne by the next dozens of generations. In fact, the calculation of SCC involves discount rate and many climate-sensitive parameters. This paper also analyzes the social cost of carbon from the perspective of the uncertainty of key parameters, but the impact of emission reduction behavior and technology investment policy have not been considered. For the further extension discussion and research of SCC, we can redefine the estimation method of carbon social cost according to the reasonable modeling of different carbon cycle structure. From the perspective of emission reduction rate, the correlation between national emission reduction factors and carbon social costs can be analyzed by controlling emission reduction intensity. The calculation of SCC is closely related to climate change, and the problem of climate change has great uncertainty. This uncertainty includes: the relationship between carbon concentration and temperature increment in the atmosphere, the uncertainty of socioeconomic impact, such as the definition of risk loss, the impact of geographical distribution on damage, and the intensity of government policy implementation. In addition, greenhouse gases such as carbon dioxide have long existed in the atmosphere, and the economic life of carbon dioxide has lasted for hundreds of years. It leads to the uncertainty of the cost and profitability of climate policy, which brings many difficulties to the climate policy model.

The discount rate plays a decisive role in the economic life of the damage. This paper discusses the influence of uncertainty of key parameters on welfare and disaster risk by using the IAM model, according to the uncertainty of carbon cycle model, discount rate and temperature rise-damage response function structure, the influence of the thick-tailed probability distribution of the parameters is incorporated into the model formula, and a new evaluation model of carbon social cost is established. It is found that the effect of carbon cycle and temperature adjustment makes the delay of temperature rise and the peak of damage is about 70 years behind the carbon emission time. SCC can be widely used in economic analysis of carbon emission regulations. Under the scenario of social cost of carbon, low-carbon technological innovation and abatement costs are relatively high, people will not significantly control carbon dioxide emissions in the short term. The government prefers chronic emission reductions and then gradually increases the intensity of emission reduction. Under the scenario of high social cost of carbon, the cost of damage caused by warming is too high compared to the technical and economic costs of emission reduction. Based on the principle of avoiding harm, the government tends to adopt radical emission reduction policies and drastically reduce current greenhouse gas emissions so as to achieve the purpose of controlling temperature rise. In order to ensure the carbon tax reduction effect, the tax rate of carbon tax should be higher than the marginal cost of using alternative energy or technology for reducing emissions. The carbon tax should be dynamically adjustable, which should correspond to the SCC of different scenarios under different economic emission reduction policies.

The social cost of carbon is closely related to the formulation of carbon tax policy. China's real discount rate and consumer preference are large, and its high sensitivity to climate change, which all make China's carbon social cost much higher than other countries. Based on the calculation of this model, the social cost of carbon is about 9.20 $/C in the benchmark scenario, and the social cost of carbon of China is about 16.35 $/C in the low discount rate scenario.

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